



Geographia Polonica
2022, Volume 95, Issue 3, pp. 255-274
<https://doi.org/10.7163/GPol.0235>



INSTITUTE OF GEOGRAPHY AND SPATIAL ORGANIZATION
POLISH ACADEMY OF SCIENCES
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HOW COVID-19 PANDEMIC INFLUENCED AIR QUALITY IN POLISH CITIES – LESSONS FROM THREE LOCKDOWNS

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Abstract

The aim of this study was to determine how COVID-19 pandemic influenced air quality in the chosen Polish cities. Data on nitrogen oxides, carbon monoxides, fine and coarse particulate matter concentrations from air quality monitoring stations was used to compare pollutants levels during the pandemic and in the 5-year pre-pandemic period. The impact of the pandemic on the air quality has been analysed using linear mixed effect models, adjusting for long-term, seasonal and weekly trends and meteorological conditions. Results showed that during the pandemic, until the second lockdown only nitrogen oxides levels were significantly reduced (up to 20%), while when again loosening restrictions the rebound effect led to 20-30% increase of all analysed pollutants.

Key words

air pollution • COVID-19 • lockdown • nitrogen oxides • carbon monoxide • particulate matter

Introduction

The COVID-19 pandemic has affected lives of many people all over the world. First cases of a new disease were reported in Wuhan, Hubei Province of China on December 12,

2019. On January 7, 2020, a previously-unknown coronavirus had been identified as an agent for the ongoing outbreak of the disease. In following weeks first imported cases of the new coronavirus disease had been detected in numerous countries, including

Thailand, Japan, Germany, Canada and USA. Following a rapid global outburst of infection in February and March, on March 11 COVID-19 had been declared a pandemic by World Health Organisation (CDC, 2021).

The first case of COVID-19 in Poland had been officially confirmed on March 4, 2020 (Ministry of Health, 2020). For the first week afterwards daily number of new cases stayed below 10. Polish government quickly undertook legislative steps to reduce possible spread of the virus, introducing the first lockdown from March 12. It included the closure of all educational institutions, as well as numerous cultural institutions like theatres, cinemas, libraries and museums. It was also strongly recommended to introduce remote work wherever possible. Despite government's efforts daily number of new cases continued to grow, reaching triple-digit value on March 21, 2020. Additional restrictions had been implemented from April 1, 2020, including limited number of customers in shops, closure of the most of service points, parks and recreational areas, along with the curfew for underage (the ban for people under the age of 18 to stay in public space without the company of an adult). Some of the restrictions were lifted at the end of April and most of them on June 6, 2020. Because of the introduced lockdown, from April till late July the daily number of new cases stayed below 500, but then began to rise, peaking at 903 new cases on August 21, 2020. That Spring and Summer spread of coronavirus is often marked as the so-called "first wave" of the pandemic in Poland (Chief Sanitary Inspectorate, 2021).

Due to spiking number of new cases (over 10 thousand on October 21, 2020 and over 20 thousand new cases on October 29, 2020), the government decided to introduce a second lockdown on November 9, 2020. It was preceded by a maximum of 27,875 new cases of COVID-19 on November 7, indicating a peak of the so-called "second wave". The second lockdown resulted in closure of all elementary and secondary schools, cultural institutions, limited number of people allowed

in churches and shops as well as shopping malls closure (which were later temporarily reopened in December). The lockdown proved to be successful, with daily number of new cases gradually dropping to 2-7 thousand in the second half of January 2021. Shopping malls and some cultural institutions were fully reopened on February 1, 2021, although some restrictions still applied (i.e. bars and restaurants only allowing take-out orders).

Daily number of new cases of COVID-19 started to rise again abruptly in the second half of February 2021, foreshadowing the so-called "third wave" of the pandemic. It had two distinctive peaks of over 35 thousand cases, on March 26 and April 1, 2021. On March 27 the government introduced a third lockdown, again closing shopping malls and limiting number of people allowed in shops, churches and other institutions, as well as forbidding public gatherings of more than five people. Nurseries and kindergartens were closed for general public (only medical and public service staff's children were admitted) and schools of all levels provided only remote teaching. Restrictions were being lifted gradually from April 19, 2021 to May 29, 2021.

The COVID-19 pandemic and associated lockdowns resulted in changes in people's mobility, affecting it in multiple ways (Parr et al., 2020). Due to sudden closure of schools at the beginning of pandemic many parents had to stay at home with their children, as they were unable to find a caregiver. Some of workplaces had been closed initially, but later many companies adapted to remote work, as lockdowns progressed and further restrictions have been introduced (i.e. a so-called "national quarantine" and stay-at-home orders). Additionally, the government introduced ad hoc legislation allowing for some public services and administrative procedures to be undertaken remotely, further reducing the necessity to leave homes. Closure of shopping malls and other points of interest also resulted in more people staying at home. Since daily commute is one of main sources of traffic (USDT, 2010), changes in people's mobility could have affected concentration

of certain air pollutants produced by Internal Combustion Engine vehicles.

Despite the relatively short time span of the COVID-19 pandemic, many researches have already been conducted to determine the impact of this event on air pollution and air quality. Various approaches were applied, depending on the availability of the data. In the majority of cases the atmospheric concentration of NO_2 has been used as the main indicator of air pollution, for its strong correlation with traffic intensity and for being one of the most commonly measured pollutants (Marinello et al., 2021). Many researches present pandemic-related changes in concentration of both gaseous emissions like NO_2 and SO_2 as well as particulate matter like PM_{10} or $\text{PM}_{2.5}$ (e.g. Berman & Ebisu, 2020; Kerimray et al., 2020; Silver et al., 2020; Adam et al., 2021; Gao et al., 2021). In some works air quality was inferred from remote sensing data, i.e. satellite imagery products from MODIS or TROPOMI (Filonchik et al., 2021a, 2021b; Hammer et al., 2021; Venter et al., 2020; Wyche et al., 2021).

Numerous studies show that lockdowns caused air pollution to decrease (Brimblecombe & Lai, 2020; Dong et al., 2021; Dutheil et al., 2020; Gautam, 2020; Liu et al., 2021; Rodríguez-Urrego & Rodríguez-Urrego, 2020; Rossi et al., 2020; Skirienė & Stasiškienė, 2021; Varga-Balogh et al., 2021). However, many of them have only considered the first lockdown, happening between March and May 2020 in most countries (e.g. Baldasano, 2020; Cameletti, 2020; Collivignarelli et al., 2020; Piccoli et al., 2020; Sharma et al., 2020; Singh & Chauhan, 2020; Moreda-Piñeiro et al., 2021). Therefore, it is important to determine whether subsequent lockdowns introduced as a response to “waves” of the pandemic had a similar effect. To our knowledge, so far there has been no studies providing a complex analysis of how multiple lockdowns impacted air pollution in European cities during the COVID-19 pandemic.

In virtually all researches, the reduced concentration of air pollutants during lockdowns has been determined through a comparison

of air quality and pollution data from lockdowns and a pre-pandemic reference period. In many cases only the single year preceding the COVID-19 outbreak (2019) has been used as a reference (Chen et al., 2021; Dantas et al., 2020; Kumari & Toshniwal, 2020; Parr et al., 2020; You et al., 2021). In others a reference period has been defined through averaging data from a few consecutive years prior to the pandemic (Chen et al., 2020; Connernton et al., 2020; Ginzburg et al., 2020; Kerimray et al., 2020; Zangari et al., 2020).

Typically, the concentrations of air pollutants, especially particulate matter, show a distinct seasonal pattern in Polish cities. In winter, air temperature drops are accompanied by increases in particulate matter levels, related to the rising heating intensity (Nidzgorska-Lencewicz & Czarnecka, 2015). Various studies show that the weather affects air quality and the concentration of pollutants (Nidzgorska-Lencewicz & Czarnecka, 2015; Cichowicz et al., 2017; Jędruszkiewicz et al., 2017; Kamińska, 2019; Xu et al., 2019; Kalbarczyk & Kalbarczyk, 2020; Zhu et al., 2021), and deterioration of air quality is usually associated with the occurrence of unfavourable weather conditions (Reizer & Juda-Rezler, 2016). Although level of nitrogen oxides is strongly positively correlated with the intensity of road traffic, it is generally most dependent on meteorological factors (Cichowicz et al., 2017), among which the increase in wind speed, that stimulates mixing processes and enables dispersion of air pollution, proved to be the most important (Kamińska, 2019; Kalbarczyk & Kalbarczyk, 2020). The air quality can also improve under wet deposition conditions, as suggested by high negative correlations between rainfall and air pollution found in Polish cities (Jędruszkiewicz et al., 2017).

Yet there have only been few researches so far that tried to evaluate the influence of meteorological conditions during a lockdown on air pollution, in addition to the impact of pandemic-related mobility restrictions themselves (Bolaño-Ortiz et al., 2020; Fu et al., 2020; Dabbour et al., 2021; Gao et al., 2021;

Gkatzelis et al., 2021). Some studies focus on how certain meteorological elements (i.e. the air temperature, downward UV radiation, humidity) or phenomena (i.e. thermal inversion) can influence the number of COVID-19 cases (Higham et al., 2021; Keikhosravi & Fadavi, 2021; Werner et al., 2021). There has also been an attempt to use a chemistry transport model to determine the impact of the lockdown on the atmosphere's composition, while offsetting meteorological conditions (Menut et al., 2020). A different approach applied machine learning tools to offset meteorological conditions during the lockdown in Wuhan (Cole et al., 2020). In another study, artificial neural networks were used to model possible air quality improvement depending on lockdowns' severity and length (Tadano et al., 2021).

It should be noted that not in all cases introducing mobility restrictions and "stay at home" order resulted in an improvement of the air quality. Some studies showed no significant change in the average concentration of air pollutants like NO₂, ozone or PM_{2.5} (Jia et al., 2020; Sicard et al., 2020), while others observed increased concentration of SO₂ during lockdown, mostly attributed to changes in power generation and not to traffic-related sources (El-Sayed et al., 2021). There have been cases of increased ozone pollution due to reductions in NO emission caused by the lockdown (Briz-Redón et al., 2021; Jephcote et al., 2021; Ropkins & Tate, 2021). In some cases, decreased concentrations of pollutants during lockdowns have been overwhelmed by unfavourable weather conditions that still caused severe air pollution events, even while the traffic was significantly reduced (Wang et al., 2020)

Few papers show the impact of COVID-19 mobility restrictions on air quality in Poland. They focus on the first lockdown only and use either satellite data (Filonchik et al., 2021a, 2021b; Grzybowski et al., 2021) or ground data from air quality monitoring stations (Rogulski & Badyda, 2021) and mobile measurements (Polednik, 2021) to investigate changes in air pollutants concentration

during one particular period of time. Therefore, it is crucial to check what changes in air quality have occurred as the COVID-19 pandemic unfolded and verify whether introduced administrative regulations had the same impact on air pollution during three subsequent lockdowns in Poland.

The aim of this study was to determine how the concentration of certain air pollutants, i.e. nitrogen oxides (NO_x), carbon monoxides (CO), coarse (PM₁₀) and fine particulate matter (PM_{2.5}), in the selected 12 Polish cities has changed during multiple COVID-19 lockdowns, including imposed mobility and service activities restrictions. Consecutive phases of the pandemic were compared to the corresponding periods in the preceding 5 years (2015-2019), taking into account the long-term, seasonal and weekly trends of particular pollution concentrations. Moreover, to account for the possible confounding factors, mean daily air temperature and wind speed, as well as the type of monitoring station surroundings were included in the analysis as covariates.

Materials and methods

Study period

The study period covered one "pre-pandemic" and seven "pandemic" periods from January 1, 2015 to April 18, 2021. The first coronavirus infection in Poland was confirmed on March 4, 2020. Since March 12, the government announced an epidemic emergency state and with the closure of educational and cultural institutions the first lockdown began (Website of the Republic of Poland, 2021). Table 1 presents the 8 phases together with a description of the preventive measures and administrative restrictions introduced in response to changing COVID-19 incidence and death rates. In the analysed period, lockdowns were introduced three times, with a complete shift to distance learning in schools and universities, the closure of cultural institutions, sports and large commercial facilities. The limited mobility of citizens lead to significant traffic reduction (Warsaw Municipal Roads Management, 2021).

Table 1. The calendar of the pandemic in Poland and the division into analysis phases

Phase no.	Period	Description
1	01.01.2015- -11.03.2020	“Pre-pandemic” period
2	12.03.2020- -19.04.2020	First lockdown: closure of educational institutions, a ban on gatherings of more than two people, limit of people in public transport and shops, limitations in going outside and in participation in religious ceremonies. Further restrictions from April 1: the closure of the most service points, parks and recreational areas, along with the ban for people under the age of 18 to stay in public space without the company of an adult. Suggestions to introduce remote work wherever possible.
3	20.04.2020- -05.06.2020	Gradual loosening restrictions: opening up forests and parks, increasing the limit of people in shops and churches. Since May 4, opening shopping malls, resuming hotel operations, allowing gradual opening of nurseries, kindergartens and cultural institutions, followed by the return of the youngest primary school students to stationary education, the opening of state offices, sports centres and restaurants.
4	06.06.2020- -23.10.2020	Removing most of the restrictions: since June 27 until August 31, 2020 lasted summer school holidays. From September 1, stationary education was allowed (with the exception of universities), and only regionally were imposed limits of people in trade, cultural activities and gatherings.
5	24.10.2020- -08.11.2020	Introduction of the restrictions for the whole country: introducing distance learning for the majority of school students and prohibiting children under 16 from going outside, unless they are accompanied by an adult. Restaurants, gyms and swimming pools were closed. Limitation of gatherings to 5 people and suggestions for employers to introduce remote work.
6	09.11.2020- -17.01.2021	Second lockdown: complete closure of schools, cultural institutions and shopping malls (except for the first two weeks of December). Periodic closing of kindergartens. Restrictions on trade and public transport. Allowing certain service activities to operate under the strict sanitary regime. Cancellation of trips for winter school holidays, under suspension of hotels and ski slopes operation (since December 28, 2020).
7	18.01.2021- -26.03.2021	Gradual loosening restrictions: restoration of full-time teaching for the youngest students of primary schools. Opening of shopping malls, cultural institutions and swimming pools under sanitary regime. From February 12, 2021 ski slopes and hotels were opened.
8	27.03.2021- -18.04.2021	Third lockdown: closure of schools, nurseries and kindergartens, cultural institutions, sport centres, shopping malls, hairdressing and cosmetic salons, furniture stores. More strict limits of people in shops and post offices. Suggestions to introduce remote work.

Air pollution data

The analysis covered 12 out of the 15 most populated cities in Poland, where complete measurement series of at least 3 out of 4 analysed pollutants (NO_x , CO, PM10 and PM2.5) were recorded at one spot over a long enough period of time since 2015. All studied towns are important cultural and administrative centres in their region, providing numerous jobs and education at all levels. Each of the cities, just before the outbreak of the pandemic, had more than 200,000 inhabitants and its population density ranged from 3469 pers./km² in Warszawa to 1362 pers./km² in Częstochowa (Tab. 2) (Statistics Poland, 2021).

In order to characterize aerosanitary conditions in Polish agglomerations in the studied period (01.01.2015-18.04.2021), hourly means of NO_x , CO, PM2.5 and PM10 concentration were obtained from 12 air quality monitoring stations of the Chief Inspectorate of Environmental Protection (GIOŚ), located within the borders of the selected cities. Each city was represented by one measuring spot in order to ensure equal representativeness of individual cities in the model. Two types of automatic urban stations were included in the study: 6 traffic stations – located in close proximity to busy roads and monitoring the level of pollution caused mainly by traffic

Table 2. Population of the studied cities; as of January 1, 2021 (Statistics Poland 2021) and air quality monitoring stations characteristics

City name and acronym	Population	Population density per km ²	Polish Air Quality System identification number	Geographical location (WGS84)	Station type	Measured pollutants
Bydgoszcz (BDG)	346,739	1,955	KpBydPIPozna	Φ 53.121774 λ 17.987883	traffic	NO _x , CO, PM ₁₀ , PM _{2.5}
Białystok (BIA)	297,585	2,908	PdBialWaszyn	Φ 53.126689 λ 23.155869	background	NO _x , CO, PM _{2.5}
Częstochowa (CZE)	219,278	1,362	SlCzestoArmK	Φ 50.817217 λ 19.118997	traffic	NO _x , CO, PM ₁₀
Gdańsk (GDA)	471,525	1,797	PmGdaLeczko8	Φ 54.380279 λ 18.620274	background	NO _x , CO, PM ₁₀ , PM _{2.5}
Gdynia (GDY)	245,867	1,813	PmGdyPoreb04	Φ 54.560836 λ 18.493331	background	NO _x , CO, PM ₁₀
Kraków (KRA)	780,981	2,386	MpKrakAlKras	Φ 50.057678 λ 19.926189	traffic	NO _x , CO, PM ₁₀ , PM _{2.5}
Łódź (LDZ)	703,186	2,390	LdLodzGdansk	Φ 51.775411 λ 19.4509	background	NO _x , CO, PM ₁₀
Lublin (LUB)	339,547	2,296	LbLubObywate	Φ 51.259431 λ 22.569133	background	NO _x , CO, PM ₁₀ , PM _{2.5}
Radom (RAD)	210,532	1,872	MzRadTochter	Φ 51.399084 λ 21.147474	background	NO _x , CO, PM ₁₀ , PM _{2.5}
Toruń (TOR)	201,106	1,716	KpToruKaszow	Φ 53.017628 λ 18.612808	traffic	NO _x , CO, PM ₁₀
Warszawa (WAW)	1,793,579	3,469	MzWarAlNiepo	Φ 52.219298 λ 21.004724	traffic	NO _x , CO, PM ₁₀ , PM _{2.5}
Wrocław (WRO)	643,782	2,192	DsWrocAlWisn	Φ 51.086225 λ 17.012689	traffic	NO _x , CO, PM _{2.5}

and 6 background stations – located within residential areas, characterizing emissions caused primarily by households. Industrial monitoring stations were excluded from the analysis, as their number in the biggest cities in Poland is too small. A full list of monitoring points, including their geographical location, Polish Air Quality System identification number and characteristic is shown in Table 2.

Meteorological data

Weather conditions that might have affected the concentration of air pollutants were described in this project by the air temperature (°C, 2 m AGL), wind speed (m/s, 10 m AGL) and total precipitation (mm). All weather data have been acquired from the

ERA5-Land reanalysis (Muñoz Sabater, 2019) with an hourly resolution, from January 1, 2015 (beginning of the comparison period) to April 19, 2021 (the end of the last lockdown described in this study). The closest grid points of the reanalysis, corresponding to the air quality monitoring stations' location, were used. Meteorological data have been processed in R software. Air temperature was converted from Kelvins to degrees Celsius, total precipitation was converted from meters to millimetres of water column, while wind speed was calculated from eastward (U) and northward (V) wind components following the formula (ECMWF, 2021):

$$|\vec{v}| = \sqrt{U^2 + V^2}$$

Data analysis and statistics

From the hourly time series data, daily mean and maximum values were calculated for the pollutants (NO_x , CO, PM_{2.5}, PM₁₀) as dependent variables for subsequent analyses. As predictors, daily mean hourly air temperatures and wind speed were computed as well. Dichotomizing precipitation, we included a binary predictor scoring a day with precipitation, if the total daily precipitation exceeded 1 mm. For the long-term trend assessment, we counted the days from the beginning of the measurement period with day 1 referring to 01.01.2015, which were then converted into years by dividing the day number by 365.25. Seasonal and weekly trends were assessed by month of the year and day of the week, respectively. In addition, days which were neither national holidays nor weekends were classified as ‘labour days’. The city and type of the weather station (traffic or background) were considered as factors. Finally, days were categorized according to the date into the phases defined in Tab. 1, contrasting the pre-pandemic period (phase 1) with the different phases (2-8) of the pandemic.

As the daily mean and maximum values of the pollutants were skewed, the log-transformed dependent variables were analysed for the effect of the pandemic phases in contrast to the pre-pandemic period by linear mixed effects models (Pinheiro & Bates, 2000) with random intercept and slope of long-term trend for city, while adjusting for seasonal (month) and weekly (day of week) cycles, for the effects of the monitoring station type, of labour days, days with precipitation, and daily mean wind speed and air temperature. A first-order autoregressive error structure was assumed for considering the serial correlation within the time series.

The mixed models were fitted with the R statistical computing environment (R Core Team, 2021) using the package *nlme* (Pinheiro et al., 2021). The effects of the pandemic phases on pollutant concentrations compared to the pre-pandemic period were obtained from the fitted mixed models

using the package *emmeans* (Lenth, 2021), which delivered the corresponding contrasts with 95% confidence intervals (CI) adjusted for multiple comparisons by the Dunnett procedure. The resulting differences were expressed as percentage change computed as $\% \text{change} = (\exp(x)-1) \cdot 100$, with x denoting the values of the estimated contrasts for the log-scaled dependent variables and their adjusted 95% CI, respectively.

Another set of mixed models was fitted additionally including the interaction of the phases with the type of the weather station allowing for calculating the contrasts (% change) stratified for the station type (traffic or background).

Results

The concentrations of analysed pollutants, especially particulate matter, showed a clear seasonal pattern in Polish cities, as exemplified for the data from Bydgoszcz (BDG) and Lublin (LUB) in Figure 1. During the COVID-19 pandemic in Poland, this seasonal trend still prevailed in case of PM_{2.5} and PM₁₀ pollution at most analysed monitoring stations, but was less pronounced for NO_x and CO concentrations exhibiting more even distributions over the year (Fig. 2). The NO_x pollution was also characterized by the largest range of variation among all analysed pollutants.

During the pandemic in Polish cities (phases 2-8), mean hourly concentrations of all analysed pollutants were lower than in 5-year pre-pandemic period (after Tab. 3). The most significant decrease was observed for NO_x on traffic stations, where mean hourly values were on average 24.3% lower than in the pre-pandemic period. In the two largest cities, Warszawa (WAW) and Kraków (KRA), the average decrease in hourly NO_x concentrations from pre-pandemic levels was 35% and 28%, respectively. Interestingly, the opposite direction of changes in pollutant concentrations was observed in Gdańsk (GDA) and Gdynia (GDY), where PM₁₀ levels were on average 10% and 24% higher, than in pre-pandemic period.

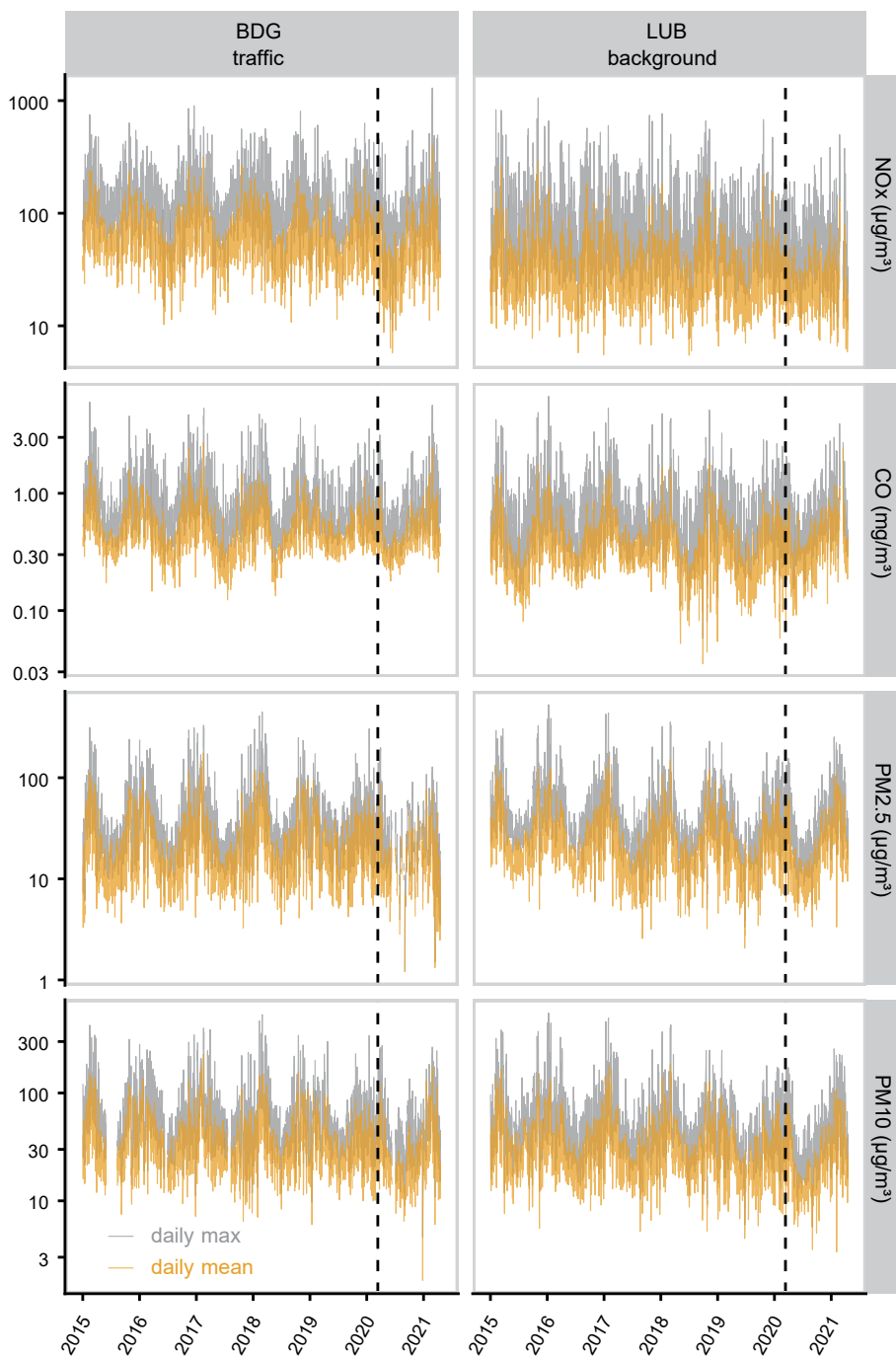


Figure 1. Daily mean and maximum hourly pollutant concentrations measured between 01.01.2015 and 18.04.2021 in Bydgoszcz (BDG, left panel) and Lublin (LUB, right panel) as examples for traffic and background monitoring stations, respectively, with the vertical reference lines denoting the transition from the pre-pandemic to pandemic phases

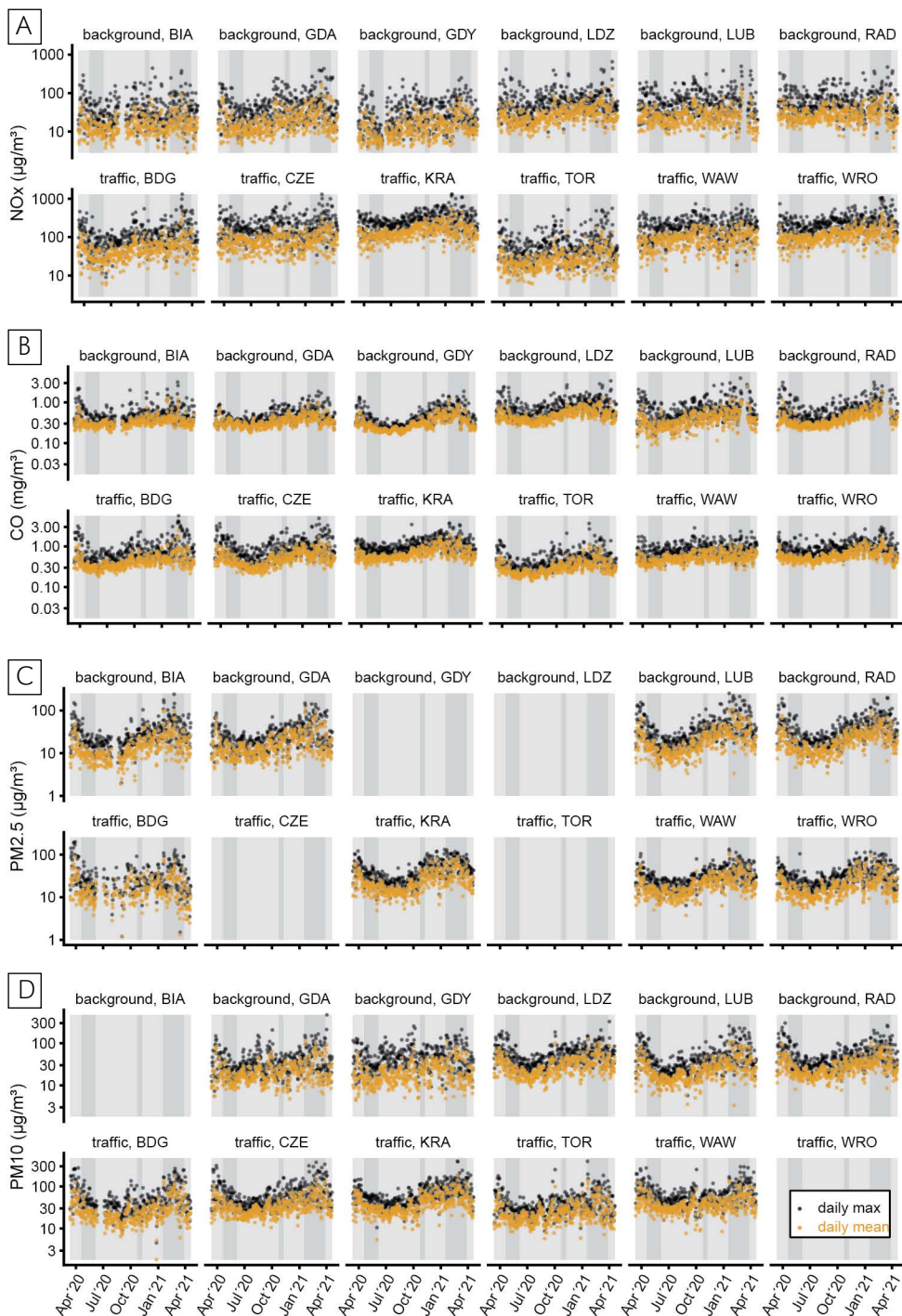


Figure 2. Daily mean and maximum hourly concentrations of the pollutants NO_x (A), CO (B), $\text{PM}_{2.5}$ (C and PM_{10} (D) measured during the pandemic period between 12.03.2020 and 18.04.2021 at background and traffic monitoring stations in twelve Polish cities (with abbreviations as in Table 2). Grey shaded periods indicate even pandemic phase numbers (2, 4, 6 and 8 in light grey) and odd numbers (3, 5, 7 in dark grey), respectively. Time range of the phases as in Table 1

During the COVID-19 pandemic period covered by this analysis, both traffic and background stations recorded lower average air temperature (on average 0.8°C and 0.6°C respectively) and slightly lower wind speed than in the 5-year pre-pandemic period (Tab. 4). This may indicate that meteorological conditions during the pandemic

(phases 2-8) were on average more conducive to the accumulation of pollutants than in the reference pre-pandemic period, which could have an impact on the outcome and therefore was consequently adjusted for by the statistical modelling.

Figure 3 summarizes the percentage change in daily mean (Fig. 3A) and maximum

Table 3. Means (SD) of daily **mean** hourly air pollutant concentrations measured during pre-pandemic and pandemic periods summarized for all stations as well as stratified for station type and city, respectively. (NA denotes missing statistics)

	NOx [$\mu\text{g}/\text{m}^3$]		CO [mg/m^3]		PM2.5 [$\mu\text{g}/\text{m}^3$]		PM10 [$\mu\text{g}/\text{m}^3$]	
	<i>pre-</i>	<i>pandemic</i>	<i>pre-</i>	<i>pandemic</i>	<i>pre-</i>	<i>pandemic</i>	<i>pre-</i>	<i>pandemic</i>
Overall	69 (71)	54 (54)	0.48 (0.27)	0.45 (0.22)	24 (19)	20 (14)	34 (25)	30 (19)
Station type								
Background	27 (21)	22 (16)	0.39 (0.19)	0.38 (0.18)	21 (17)	19 (14)	28 (20)	26 (16)
Traffic	111 (79)	84 (60)	0.58 (0.31)	0.52 (0.24)	28 (22)	21 (14)	40 (29)	34 (21)
City								
BDG	63 (34)	51 (38)	0.49 (0.24)	0.44 (0.23)	23 (19)	17 (13)	36 (24)	29 (22)
BIA	18 (12)	16 (12)	0.37 (0.12)	0.34 (0.13)	17 (13)	15 (12)	NA	NA
CZE	92 (62)	81 (43)	0.53 (0.33)	0.52 (0.23)	NA	NA	40 (31)	36 (20)
GDA	25 (21)	21 (18)	0.37 (0.14)	0.34 (0.11)	13 (9)	17 (13)	20 (12)	22 (16)
GDY	17 (13)	14 (11)	0.32 (0.16)	0.32 (0.14)	NA	NA	17 (11)	21 (15)
KRA	197 (79)	142 (69)	0.85 (0.39)	0.69 (0.27)	38 (28)	25 (15)	57 (38)	41 (23)
LDZ	34 (22)	29 (17)	0.51 (0.21)	0.49 (0.17)	25 (19)	NA	35 (22)	30 (17)
LUB	34 (26)	25 (15)	0.36 (0.21)	0.39 (0.21)	24 (18)	21 (16)	32 (21)	25 (17)
RAD	33 (21)	29 (15)	0.43 (0.20)	0.41 (0.20)	25 (18)	21 (13)	34 (21)	29 (16)
TOR	34 (24)	28 (22)	0.36 (0.15)	0.31 (0.14)	NA	NA	26 (16)	26 (17)
WAW	139 (71)	90 (45)	0.59 (0.20)	0.54 (0.17)	25 (15)	20 (13)	41 (20)	39 (20)
WRO	132 (58)	112 (54)	0.63 (0.23)	0.61 (0.21)	24 (19)	20 (13)	NA	NA

Table 4. Daily mean (SD) of hourly values of air temperature and wind speed, respectively, and of daily total precipitation measured during pre-pandemic and pandemic periods summarized for all stations as well as stratified for station type

	Air temperature [°C]		Wind speed [m/s]		Total precipitation [mm]	
	<i>pre-</i>	<i>pandemic</i>	<i>pre-</i>	<i>pandemic</i>	<i>pre-</i>	<i>pandemic</i>
Overall	9.5 (8.4)	8.7 (8.2)	3.3 (1.3)	3.1 (1.1)	2.1 (3.7)	2.2 (4.1)
Station type						
Background	9.1 (8.5)	8.5 (8.2)	3.2 (1.3)	3.0 (1.1)	2.2 (3.8)	2.4 (4.4)
Traffic	9.8 (8.2)	9.0 (8.1)	3.4 (1.3)	3.2 (1.1)	1.9 (3.6)	2.0 (3.8)

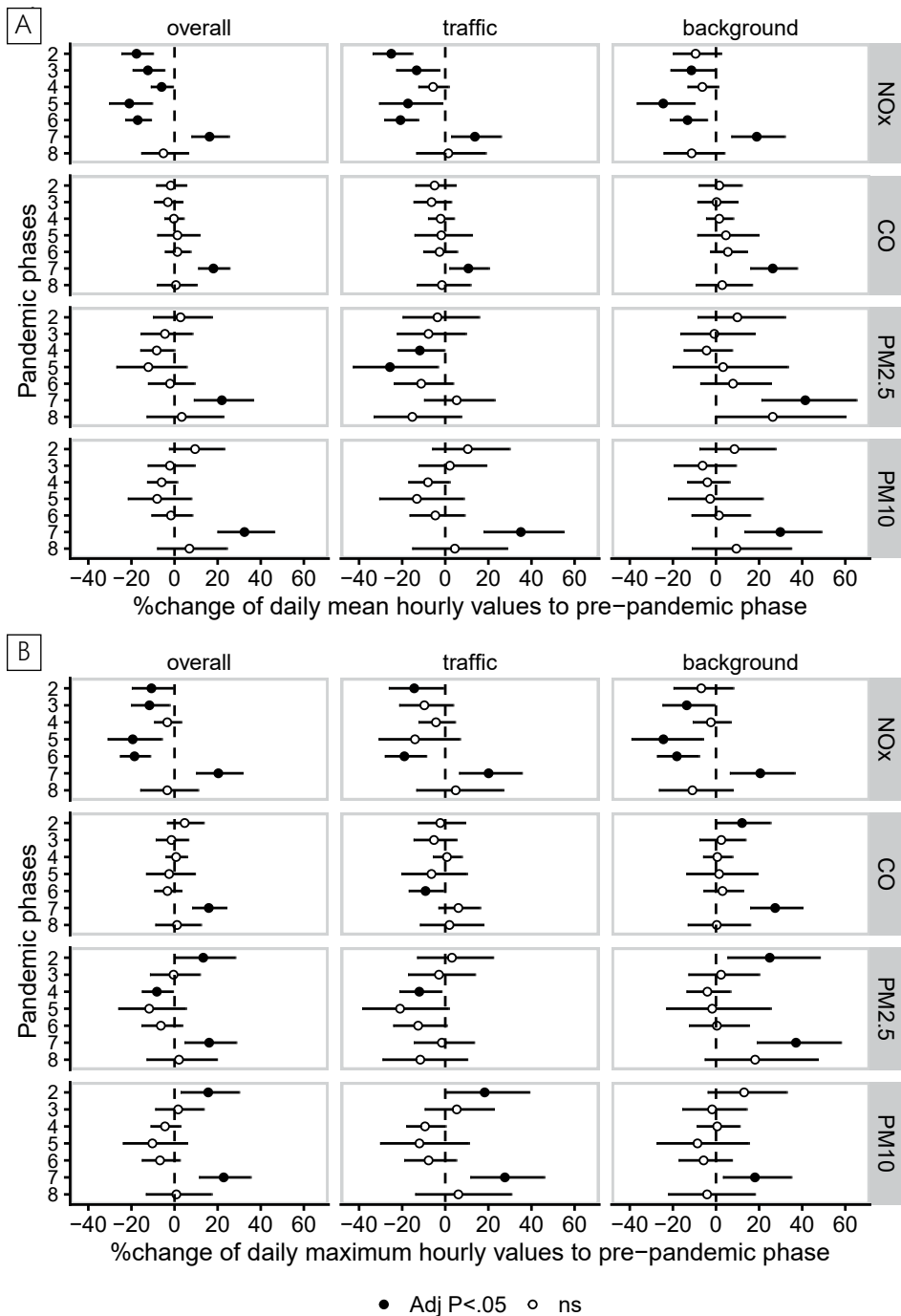


Figure 3. Estimated percentage change of daily A) **mean** and B) **maximum** hourly concentrations of the pollutants NO_x, CO, PM_{2.5} and PM₁₀ in the pandemic phases 2-8 (Tab. 1) compared to the pre-pandemic period for the overall effect from all stations and stratified by station type (traffic, background). Error bars indicate the 95% CI adjusted for multiple comparisons by the Dunnett procedure, with open symbols marking statistically non-significant (ns) effects and filled symbols indicating statistically significant effects, respectively

(Fig. 3B) hourly pollutant concentrations displayed as overall effect and separately for traffic and background stations, respectively. Figure 3A revealed significant reductions of the daily mean hourly values during the pandemic restrictions for NO_x only, with peak reductions of about 20% occurring during the two nationwide lockdown periods (phase 2 & 6) and the preparatory phase 5 preceding the second lockdown. No significant reductions were obtained for the other pollutants except of a reduction of $\text{PM}_{2.5}$ concentration on traffic stations in phases 4 & 5. On the other hand, in phase 7, characterized by loosening the mobility restrictions, a general strong rebound effect with significant increases of more than 30% for PM_{10} and about 20% for the other pollutants was observed, returning to pre-pandemic values in the subsequent third lockdown period (phase 8).

The corresponding effects stratified for the station type, showed slightly stronger and statistically significant NO_x reductions at traffic monitoring points. During the initial pandemic phases, traffic stations reacted earlier by reducing the average daily pollution level, but in phase 7 they showed similar patterns for the rebound effect as background stations (Fig. 3A).

The analogous results for the daily maximum hourly concentrations (Fig. 3B) largely corroborated the results observed for the daily means, though the effects were less pronounced and occasionally differed from the results for the means, e.g. by showing an initial increase during phase 2 of $\text{PM}_{2.5}$ and CO at the background stations and for PM_{10} concentrations overall.

Discussion and conclusions

The implementation of social distancing measures to control the spread of the COVID-19 pandemic had serious consequences, including changes in air quality in different countries. Drastic and sudden restrictions on the mobility and activity of millions of people resulted in significant changes in anthropogenic emissions of air pollutants, which created

an unprecedented opportunity to analyse the environmental effects of this real-world experiment (Gkatzelis et al., 2021; Onyeaka et al., 2021). The impact of the first shutdown in Spring 2020 on air quality improvement has been already demonstrated in many studies (Adam et al., 2021; Marinello et al., 2021; Skirienė & Stasiškienė, 2021). However, most of the papers published in the first months after the outbreak of the pandemic, when comparing data from the lockdown period with earlier reference observations, ignore temporal variability and long-term trends in pollutant concentrations, or do not incorporate a specific method to quantify the impact of meteorological conditions on air pollution, which could distort the interpretation of the results (Zangari et al., 2020; Gkatzelis et al., 2021).

As a consequence of stay-at-home orders and decrease in vehicle usage, especially traffic emission was limited, what resulted in much lower NO_2 and NO_x concentrations recorded all over the world (Venter et al., 2020; Briz-Redón et al., 2021; Dong et al., 2021; El-Sayed et al., 2021; Ropkins & Tate, 2021; Varga-Balogh et al., 2021; Wyche et al., 2021). However, the air quality improvement effect was not seen everywhere and for all pollutants. In Hungary, although NO_x concentrations dropped up to 45%, the PM_{10} level even slightly increased (+ 7%) at the beginning of the first lockdown and was rather weather-driven (Varga-Balogh et al., 2021). Chen et al. (2020) noticed that both NO_2 and CO levels were dropping in US cities (up to 49% and 37% respectively) and tended to increase with local population density, while significant reductions of particulate matter occurred seldom and only in those cities with highest NO_2 decline. Furthermore, increases in SO_2 concentrations in the central and southern regions of Florida were associated with higher power generation due to increased residential usage during lockdown (El-Sayed et al., 2021), while in NYC, in comparison to the same span of time in years 2015-2019 no or minimal improvements of air quality were observed (Zangari et al., 2020).

In turn, Wyche et al. (2021) observed spikes in PM_{2.5} and PM₁₀ levels alongside lockdown in March 2020 in the south-eastern regions of the UK, but these were probably caused by interregional pollution transport rather than governmental restrictions.

The impact of the restrictions introduced in Poland in response to the development of COVID-19 pandemic on air quality is ambiguous and has not been clearly defined so far. In this study we demonstrated that in general, up to the second lockdown (November 2020 – January 2021), the pandemic significantly reduced NO_x levels in large Polish cities by 6% to 21% in daily mean and by 3% to 19% in daily maximum concentrations compared to the pre-pandemic period. Similar decrease of NO₂ pollution on urban air quality stations in Poland during first lockdown (April 2020) (-20%) was observed by Grzybowski (2021), while slightly weaker effect (6-11%) was found for this period by Rogulski and Badyda (2021), which, in comparison to other European cities, represents a relatively low reduction (Solberg et al., 2021). More significant drops in NO_x concentration were recorded at traffic monitoring stations than at background stations, which has been also confirmed by the results from UK (Jephcote et al., 2021; Ropkins & Tate, 2021) and may be associated with a significant decrease in car traffic in Polish cities in the first stages of the pandemic (Warsaw Municipal Roads Management, 2021). In the case of particulate matter pollution, we observed that the overall effect of pandemic restrictions on pollution level was insignificant in the first 6 phases of the pandemic. However, during the first lockdown, we observed statistically significant increase of the daily maximum hourly values of PM_{2.5} and PM₁₀ by 13% and 16%, respectively. For the same period, Polednik (2021), as well as Rogulski & Badyda (2021), obtained consistent results from stationary measurements in Polish cities, while Grzybowski et al. (2021), on the contrary, noted significantly lower (-20%) PM_{2.5} concentration as compared to the 10-year average. Nevertheless, the authors of the latter work drew attention

to the fact that the COVID-19 lockdown was not the unique reason for the aerosol concentrations drop during spring 2020, as the meteorological conditions in this period were particularly conducive to good air quality (i.e. lower emissions and dispersion of pollutants). Therefore in our study, to calculate the impact of the pandemic restrictions on pollutants concentrations, we accounted for confounding effects of meteorological conditions and temporal trends, which could have contributed to the fact that we did not observe a reduction effect on PM_{2.5} and PM₁₀ levels during the first lockdown. On the other hand, conforming to observations in China (Gao et al., 2021), the concentration of particulate matter in Poland, especially PM_{2.5}, started to decrease later. However, this effect was statistically significant only at traffic stations in phase 4 and 5 of the pandemic, which could have been the result of a gradual adaptation of residents to the situation – switching to remote work and distant learning, resulting in less presence of people within the city.

From the beginning of 2021, pollution reductions in relation to the pre-pandemic period were no longer registered. Moreover, in phase 7, statistically significant increases (20-30%) of all analysed pollutants levels (NO_x, CO, PM_{2.5} and PM₁₀) were observed. This rebound effect could be related to the increase in the mobility of people who, after a long period of the restrictions, were tired of isolation and limited access to various types of services; hence, they began to move around the city more frequently. At the same time, the increase in pollution concentrations could alternatively be related to shift in travel mode away from public transport towards private cars as a reaction to the threat of coronavirus infection, as was observed during working days in Taiwan (Chang et al., 2021). In addition, in January 2021, the population vaccination program against COVID-19 was launched, which could have contributed to a reduction in the sense of danger in the society and an increase in social and economic activity. However, such high levels of pollution in phase 7 could be related primarily

with adverse weather conditions, which can contribute to the air quality significantly and may outweigh the benefits of emission reductions due to pandemic restrictions (Wang et al., 2020; Jephcote et al., 2021).

Despite the fact that in this study we took into account the confounding effect of air temperature, wind speed and precipitation, the meteorological conditions of the accumulation and dispersion of pollutants might have not been fully addressed. This problem requires further in-depth analyses of the thermodynamic balance of the atmosphere and the advection of air masses during COVID-19 lockdowns. Further studies might also aim to increase the spatial resolution by considering both traffic and background stations from the same city, including more industrial regions like Silesia or incorporating additional pollutants, like sulphur dioxide (SO₂). It is also suggested that more complex contributions, e.g. from resuspension and secondary aerosol may be important factors influencing changes in air pollutants levels during this period (Ropkins & Tate, 2021).

The COVID-19 pandemic and the accompanying administrative restrictions have created a unique opportunity to verify whether limitation of citizens mobility and, as a consequence, urban traffic restraint is a good strategy to improve air quality in the city. Our results demonstrate that the reduction in car traffic had a positive effect only on the reduction of NO_x concentration in Polish cities, while the overall air quality was strongly dependent on meteorological conditions and other

emission sources. Moreover, many studies prove that a decrease in NO_x concentration may result in a significant increase in tropospheric ozone level (Briz-Redón et al., 2021; Dong et al., 2021; Jephcote et al., 2021). Therefore future policy interventions to reduce emissions should take into account that limitation of individual pollutants can cause an increase in others, and may induce changes in the composition and reactivity of trace elements in the atmosphere (Wyche et al., 2021). As other studies report, during the lockdown period increases in O₃ content in troposphere enhanced the formation of secondary PM_{2.5} through the atmospheric oxidation of VOCs, what partially explains higher PM levels observed at that time in some places (Adam et al., 2021). Subsequently our study demonstrates trends in air pollution changes over the course of three lockdowns in Poland. Although citizens' mobility restrictions contributed to the improvement of air quality to a small extent, this effect was not persistent. After the first impact caused by COVID-19 pandemic outburst, during the third lockdown in 2021 emissions in Polish cities returned to pre-pandemic levels. Therefore, greater remedial actions than only traffic and production restrictions will be required to achieve the EU reduction levels and the transition to the climate-neutral economy until 2050.

Editors' note:

Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

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